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Modelling of material handling operations using controlled traffic

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Controlled-traffic farming (CTF) is a management system that can eliminate soil compaction by wheels within the cropped area. According to the principles of CTF, permanent parallel wheel tracks are created within the field area. The benefits of CTF, in terms of productivity and sustainability, have been the subject of intensive research for a number of decades. This has led to the establishment of CTF in various regions around the world. CTF also has drawbacks that include the need to purchase specialised machinery, the loss of cropped area due to dedicated wheel tracks and the cost of creating and maintaining permanent traffic lanes within the fields. Furthermore, field efficiency is affected by CTF due to significant increases in idle time of in-field transport and the way the fields are traversed in material handling operations. During fertilisation, when tramline length and the driving distance needed to apply one tanker load of fertiliser are not coordinated, CTF does not allow for random turns and requires the tanker to drive empty along the traffic path. The inherent characteristics of the CTF system, as well as the fact that cooperatively owned machines are used to carry out the operations, makes existing models inadequate for evaluating field efficiency.

In this paper, the development of a discrete-event model for the prediction of travelled distances of a machine operating in material handling operations using the concept of CTF is presented. The model is based on the mathematical formulation of the discrete events regarding the motion of the machine when performing the fieldwork pattern. To evaluate the model two slurry application experiments were designed. The experiments involved registering the position and monitoring the application status of the slurry applicator. Validation showed that the model could adequately predict the motion pattern of machinery operating in CTF. Prediction errors of total distance travelled were 0.24% and 1.41% for the 2 experimental setups. The current model structure captures the interrelationships between the mutual influencing parameters of motion sequence and configurations of the CTF layout. This model has the potential to be used for autonomous vehicles.

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1. Introduction

Controlled-traffic farming (CTF) (also known as the Tramline Farming System), is a management system that can completely eliminate soil wheel compaction within the cropped area (Chamen et al., 2003). CTF restricts soil compaction to the wheel tracks, thus providing a loose rooting zone (Hamza and Anderson, 2005). According to the CTF principles, permanent parallel wheel tracks are created within the field area. This involves modifications to the applied machinery, which also affects the overall economy (Chamen and Audsley, 1993). The main modification of CTF is matching the wheel distance widths of the implemented machinery to allow the tyres to run exclusively on the permanent wheel tracks. In recent years, navigation aids such as auto-steering systems have been introduced to accurately follow the tracks and to increase system efficiency (Harbuck et al., 2006; Batte and Ehsani, 2006).

The benefits of CTF in terms of productivity and sustainability have been investigated and documented through intensive research for a number of decades (e.g., Taylor, 1983; Tullberg et al., 2007). The yield potential of various crops when CTF is used has been documented by Chamen et al. (2006), Tullberg et al. (2001), Douglas et al. (1995) and Chamen et al. (1992). Energy savings have also been described as an important benefit of CTF (McPhee et al., 1995). Eliminating wheel damage on the cropped area of arable land leads to substantial cultivation energy savings, ranging from 37 to 70% (Chamen et al. 1992).

In addition to the benefits of increased yield and reduced energy use, Reicosky et al. (1999) reported reduced
loss of carbon dioxide and water in CTF trials. Unger (1996) showed that by restricting all traffic to specified zones, the implementation of CTF reduced the potential for developing adverse physical soil conditions under irrigated conditions.

CTF does have drawbacks, which include the need to purchase specialised machinery, the loss of cropped area due to dedicated wheel tracks and the cost of creating and maintaining permanent traffic lanes within the fields (Lagè et al., 2003). Furthermore, constraining the paths for traversing the field may decrease field efficiency. In the case of field fertilisation, the traffic lane length determines the amount of nonproductive in-field transport, and this is minimised with full coordination between the length of the tramlines and the driving distance needed to apply one tanker load. When coordination between tramline length and driving distance is not attained, CTF does not permit random turnings and requires the machine to drive empty along the traffic path. The non-working travel distance can increase even more when the refilling unit is not located in the direction that the machine is travelling when the tank empties, because the machine must execute an 180° turn upon reaching the headland and drive back along the track towards the opposite headland to refill the tank. In addition, there are cases where the machine has to travel over a part of a track without applying fertiliser, in order to reach the position where the previous application was terminated. As a result, implementing CTF for material handling operations such as harvesting and fertilising can affect field efficiency by significantly increasing non-productive in-field transport. This causes decisions regarding the operation of the machinery system to become critical.

The evaluation and prediction of agricultural machinery performance are important aspects for machinery management. By specifying and quantifying the operational performance of farm machinery, it is possible to select and plan the use of equipment in any given environment. Modelling approaches have included simulation models that comprise operations decomposition (e.g., Achten, 1997; Sørensen, 2003; Sørensen and Nielsen, 2005). Such models cover current working methods, specific conditions and the associated task times pertaining to derived norms. In addition, databases are continuously being updated as a result of new data, improved modelling techniques, new operations methods, and so on. However, the inherent features of the CTF system, including the notion that material handling operations are usually carried out by cooperative machines, make the existing models inadequate for evaluating field efficiency. Consequently, new models have to be developed for estimating the efficiency of CTF operations involving in-field transport. Such models can provide a tool for comparing CTF and conventional unconstrained traffic farming, in order to evaluate the reduction of field efficiency alongside environmental and potential economical benefits of CTF implementation.

The objective of this paper was to model the material handling operations using controlled traffic as part of the machinery management system on the farm. The model was based on the mathematical formulation of the discrete events regarding the motion of the machine when traversing the fieldwork pattern. To evaluate the model, two slurry application experiments were designed. They involved registering the position and monitoring the application status of the slurry applicator.

2. The mathematical model

2.1. Preliminary notifications

The presented model of material handling operations regards the machinery system that uses an in-field operating machine application unit (AU) cooperating with an out-of-the-field transport unit (RU). A 2-dimensional coordinate system \((x, y)\) is assigned to the field, where the \(y\)-axis is parallel to the in-field moving direction of the AU (Fig. 1). The headland that is located in the positive direction of the \(y\)-axis will be denoted as the “upper” headland, while the one that is located in the negative direction will be denoted as the “lower” headland. Similarly, when the AU is moving parallel in the positive direction of to the \(y\)-axis, it is considered to be moving “upwards”, while moving in the opposite direction it is considered to be moving “downwards” (Fig. 1).

The exclusive headland pattern used involves a given field covered by a set of parallel tracks (or trips) that begins at one

![Image](https://example.com/image.png)

**Fig. 1** – Assignment of a coordinate system at each field, and notifications concerning the AU operating motion and the track numbering with regard to this system.
2.2. Definitions of vectors and functions

2.2.1. Coordinates vectors

Let \( \mathbf{u}(x_i, y_i) \), \( \mathbf{d}(x_i', y_i') \), be the vectors of the coordinates of the upper and lower endings of each field track, respectively. We define the function \( \beta(\cdot) : \mathbb{T} \rightarrow [-1,1] \), which equals 1 if the AU is moving upwards while operating in track \( i \), and equals \(-1\) if is moving downwards. The mathematical definition of the function \( \beta \) will be given later by the use of a recursive relation. We define the vectors \( \mathbf{e}_1^i, \mathbf{e}_2^i, \mathbf{e}_3^i \), \( i \in \mathbb{T} \), as:

\[
\mathbf{e}_1^i = \begin{cases} 
\mathbf{u}, & \beta(i) = 1 \\
\mathbf{d}, & \beta(i) = -1 
\end{cases} \quad \text{and} \quad \mathbf{e}_2^i = \begin{cases} 
\mathbf{u}, & \beta(i) = -1 \\
\mathbf{d}, & \beta(i) = 1 
\end{cases}
\]

(1)

These vectors determine the location of the “entry” and “exit” for each field track in terms of the AU’s motion. Finally, let \( \mathbf{f}_0^i \) and \( \mathbf{f}_3^i \) denote the vectors of the coordinates of the location that the AU initiates and completes the application of a load during the \( n \)th sequence route of the operation.

2.2.2. Refilling unit vector

Regarding the location where refilling of the AU tank takes place, the following cases are recognized:

A. The RU is located in one of the headlands of the field.

B. The RU is located outside the field and the AU can reach it only after reaching a particular headland location (e.g., one of the field corners).

C. The RU is located outside the field and the AU can reach it by moving freely after reaching the headland.

We define the vector \( \mathbf{c}_i^j = (\mathbf{c}_1^j, \mathbf{c}_2^j, \mathbf{c}_3^j) \), where \( \mathbf{c}_1^j \in \mathbb{T}, \mathbf{c}_2^j \in \mathbb{R} \) and \( \mathbf{c}_3^j \in [-1,1] \). The element \( \mathbf{c}_1^j \) equals the track number where the RU is located in case A, while in case B it equals the index of the track from where the AU has to leave the field area. When the RU is moving to get close to the AU, the element \( \mathbf{c}_2^j \) equals the track number where the machine ends the application \( (\mathbf{c}_2^j = \mathbf{c}_3^j) \) while the other two elements both equal zero.

Element \( \mathbf{c}_3^j \) equals the out of field distance that the AU has to travel to reach the RU. Element \( \mathbf{c}_3^j \) equals 1 if the transport unit is located at the “upper” side of the field and equals \(-1\) if it is located at its “lower” side.

2.2.3. Function \( p \)

The bijective function \( p(\cdot) : \mathbb{T} \rightarrow \mathbb{T} \), which was introduced by Bochtis (2008) is used for the mathematical description of the headland pattern. Its definition determines that, for every field track, the function value \( p(i) \) returns the order in which the machine covers the \( i \)th field track. The inverse function \( p^{-1}(\cdot) : \mathbb{T} \rightarrow \mathbb{T} \) gives the traversal sequence of the field tracks by the machine. Hence, the traversal sequence for the entire field is given by the permutation \( \sigma = p^{-1}(1), p^{-1}(2), ..., p^{-1}(\|\mathbb{T}\|) \).

By using the function definition, the following can be stated:

\[
\mathbf{s}^i = \begin{cases} 
\mathbf{f}_0^i, & n = 1 \\
\mathbf{f}_3^i = e_3^{p^{-1}(i)} \mathbf{e}_3^i, & \forall n \neq 1 
\end{cases}
\]

2.2.4. Function \( \beta \)

When the AU resumes the application at the point that it was stopped during the previous route, the direction of its motion on the track \( (\mathbf{c}_3^{p^{-1}(i)} = \mathbf{c}_2^i) \) might not remain the same. This happens when the tank is getting empty and the AU is moving in the direction of the location of the RU. In this case, the formula is \( \beta(\mathbf{c}_3^i) = \mathbf{c}_2^i = 1 \).

![Fig. 2 - A completed route during the material handling operation.](image-url)
In the case where there are no changes in the field pattern during the operation, the predetermined direction of the AU in each track is given by the function:

$$\gamma(t) = (-1)^{\delta_{t}}$$  \hspace{1cm} (2)

Using the $\gamma(t)$ function, the $\beta(t)$ function that gives the actual direction of the AU during the traversal of the track $i$ that belongs to the $n$th route, will be given by:

$$\beta(i) = \gamma(i) \cdot \prod_{j=1}^{n-1} [\Delta(:,t)]$$  \hspace{1cm} (3)

Where the product incorporates the total changes occurring to the predetermined direction of the AU.

### 2.2.5. Distance operator

Let $\Delta: \mathbb{R}^2 \times \mathbb{R}^2 \rightarrow \mathbb{R}$ be the operator that returns the distance between the two points belonging to the same track, given the vectors of their coordinates. The length of track $i$ is then equal to $\Delta(u_i, \overline{d}_i)$. In the case of the CTF, where the tracks are straight vectors of their coordinates. The length of track $i$ is given by

$$\Delta(u_i, \overline{d}_i) = \sum_{k=1}^{n} \Delta(u_{ik}, \overline{d}_{ik})$$

for the upper and the lower headland respectively. The lengths of the upper and lower headlands, respectively, are given by:

$$l_{uh} = w + \sum_{k=1}^{n} \Delta(u_{ik}, \overline{u}_{ik}) \quad \text{or} \quad l_{uh} = w + \sum_{k=1}^{n} \Delta(d_{ik}, \overline{d}_{ik})$$

where $w$ (m) is the effective operating width.

### 2.2.6. Routes

The number of times that the tank on the AU is loaded, as well as the number of routes that it has to perform in order to complete the operation in the field body is given by

$$\lambda = \left[ \frac{q_w}{C} \sum_{i=1}^{n} \Delta(u_i, \overline{d}_i) \right]$$

where $C$ (m$^3$) is the capacity of the tank, and $q$ (m$^3$/s-$^2$) is the volume of the material that has to be applied per square meter of the field area and the symbol $\sum$ denotes the ceiling function.

By taking into account Eq. 5, the total effective distance during the whole operation can be written as

$$d_{tr} = 2(a_u + a_d)w + \sum_{i=1}^{n} \left[ \Delta(u_i, \overline{d}_i) + a_u \cdot \Delta(u_{ik}, \overline{u}_{ik}) + a_d \cdot \Delta(d_{ik}, \overline{d}_{ik}) \right]$$

where $a_u$ and $a_d$ are the number of passes that the AU has to perform in order to complete the application at the upper and at the lower headland, respectively.

Thus, the total number of routes (including operating in the headlands) is given by

$$\lambda = \left[ \frac{q_w}{C} \sum_{i=1}^{n} \Delta(u_i, \overline{d}_i) \right]$$

By taking into account that the material quantity needed for the remaining field area that is assigned to the final route, is not in accordance with a full load, the effective distance that the AU travels during a route is written as

$$d_{tr} = \left[ \frac{q_w}{C} \prod_{i=1}^{n} \Delta(x_{ik}, x_{ik}) \right]$$

where

$$d_{tr} = \left[ \frac{q_w}{C} \prod_{i=1}^{n} \Delta(u_{ik}, d_{ik}) \right]$$

2.3. Non-working travelled distances

#### 2.3.1. From the RU to the resuming position

The path that connects the RU and the on-the-track position where the AU resumes the application potentially includes three parts. The AU has to move from the refilling location to the headland $(\overline{d}_1)$, and next through the headland from the end of the track $(\overline{d}_3)$ to the end of the track $(\overline{d}_3)$ (or $(\overline{d}_1)$) and finally to the position where the application can resume $(\overline{d}_3)$ or $(\overline{d}_3)$.

This distance is equal to

$$d_{tr} = \left[ \frac{q_w}{C} \prod_{i=1}^{n} \Delta(u_{ik}, d_{ik}) \right]$$

where

$$d_{tr} = \left[ \frac{q_w}{C} \prod_{i=1}^{n} \Delta(u_{ik}, d_{ik}) \right]$$

and is given by (Bochtis, 2008):

$$d_{tr} = l_{uh} = w + \sum_{k=1}^{n} \Delta(u_{ik}, \overline{u}_{ik}) \quad \text{or} \quad l_{uh} = w + \sum_{k=1}^{n} \Delta(d_{ik}, \overline{d}_{ik})$$

where $w$ (m) is the effective operating width.

#### 2.3.2. During the application

The effective distance that the AU has to travel in the course of a route is given by

$$d_{tr} = \left[ \frac{q_w}{C} \prod_{i=1}^{n} \Delta(u_{ik}, d_{ik}) \right]$$

The distance that the AU travels during the effective part of the route consists of the effective distance as well as of the non-working distance during the headland turns (except of the case that the effective distance is less than the length of the track). From the definition of the function $p(\cdot)$ as well as its inverse function, the $k$th field tracks that the machine traverses during the route $n$ ($k = p(\overline{d}_3) - p(\overline{d}_3)$) can be written as follows:

$$p^{-1}[p(\overline{d}_3) + 0]$$

$$p^{-1}[p(\overline{d}_3) + 1]$$

$$\vdots$$

$$p^{-1}[p(\overline{d}_3) + k_n - 1]$$

Note that in order to comply with the common structure, for all elements of the sequence, the first element $\overline{d}_3$ must be rewritten as $p^{-1}[p(\overline{d}_3) + 0]$. During the effective part of the route, the AU has to perform $k_n - 1$ headland turns. Using the previous formulation, the total non-working distance during these turns is given by

$$d_{tr} = \sum_{i=1}^{k_n-1} L_{min}(p^{-1}[p(\overline{d}_3) + i] - p^{-1}[p(\overline{d}_3) + (i + 1)])$$

where

$$L_{min}(i - j)$$

returns the theoretical travelling distance for the transition of the AU from field track $i$ to field track $j$ and is given by (Bochtis, 2008):

$$L_{min} = \left\{ \begin{array}{ll}
X_{min}(i - j), & |i - j| < 2r_{min}/w \\
H_{min}(i - j), & |i - j| \geq 2r_{min}/w
\end{array} \right.$$
where $r_{\min}$ is the minimum turning radius of the machine and $X_{\theta} (T_\theta)$. The symbols $\Omega$, $\Pi$ and $T$ refer to the most common manoeuvres for an agricultural machine operating in a headland pattern, namely, the loop (or forward turn), the double round corner turn and the reverse (or switch-back-turn), respectively (Hunt, 2001). The minimum length for any of these turn types can be computed by the following expressions, that were derived based on the kinematic equations of motion for a non-holonomic vehicle (Bochtis and Vougioukas, 2008):

\begin{align}
\Omega_{\min} (i-j) &= r_{\min} \left[ 3\pi - 4\sin^{-1}\left(\frac{2r_{\min} + |i-j| \cdot w}{4r_{\min}}\right) \right] \\
T_{\min} (i-j) &= r_{\min} (2\pi + |i-j| \cdot w) \\
\Pi_{\min} (i-j) &= (|i-j| \cdot w + (\pi - 2)r_{\min}) \quad (14)
\end{align}

2.3.3. From the field track to the RU
The total effective distance during a route, can also be written as

\[ d_{\theta} = \Delta(o^\theta, e_i^\theta) + \sum_{i=\theta}^{p-1}[e_i^\theta, e_{i+1}^\theta] + \Delta(e_{p-1}^\theta, f^\theta) \]  

(15)

The term $\Delta(e_{p-1}^\theta, f^\theta)$ gives the distance that the AU travels on the last track of the route $n$. The remaining distance that it has to travel on the current track in order to reach the headland is given by

\[ d_{\theta} = \Delta(u^\theta, d^\theta) - d_{\theta} + \Delta(e_i^\theta, e_{i+1}^\theta) + \sum_{i=p-1}^{\theta}[e_i^\theta, e_{i+1}^\theta] + \Delta(u^\theta, d^\theta) \]  

(16)

Regarding the travel of the AU from the end of the last track of route $n$ to the RU, there are two possible cases:

(A). The AU is directed to the position of the RU at the time the interruption occurs ($\beta_{j}^{(f_1)+} \cdot \beta_{j}^{(f_2)} = 1$). In this case, the AU has to traverse the headland from the end of track $f_1$ to the end of track $f_2$, and then has to cover the path from this point to the RU position ($v_2$). The total travelled distance is shown by

\[ d_{\theta} = u_{1}^{\theta} + e_{i}^{\theta} + \sum_{i=\theta}^{k-\min \{\beta_{f_1}, \beta_{f_2}\} - 1} \Delta(u_{1}^{\theta}, u_{i}^{\theta}) + \Delta(e_{i}^{\theta}, e_{i+1}^{\theta}) + \Delta(u_{1}^{\theta}, e_{i}^{\theta}) + \Delta(e_{i}^{\theta}, e_{i+1}^{\theta}) + \Delta(u_{1}^{\theta}, d_{\theta}^{\theta}) + \Delta(d_{\theta}^{\theta}, v_{2}) \]  

(17)

(B). The AU is directed in the opposite direction to the position of the RU ($\beta_{j}^{(f_1)-} \cdot \beta_{j}^{(f_2)} = -1$). In this case, the AU has to perform the following sequence of motions; travelling to the end of the current track ($v_1$), executing a headland turn, travelling along the selected track to the opposite headland, travelling on the headland in order to reach the end of track $v_1$ and finally travelling to the position of the RU for a distance $v_2$.

When the AU reaches the end of track $v_1$, in order to perform a smooth turn (II-turn), the distance between the two tracks should be greater or equal to $2r_{\min}/w$. By considering

![Fig. 3 – Basic architecture of the model.](image)

![Fig. 4 – System setup of the test design.](image)
this, the number of the track that the AU enters after the turn is the following:

\[ v = e_i^t \pm \left( \frac{2r_{\text{min}}}{w} \right) + 1 \]  

(18)

Where the positive sign is referring to the case \( e_i^t \geq e_j^t \), while the negative sign denotes the inverse case. The manoeuvring length is given by \( H(\frac{2r_{\text{min}}}{w}) + 1 \).

Next the total distance in this case is given by:

\[
\begin{align*}
\bar{d}_{r \rightarrow t} &= \begin{cases} \\
\bar{d}_{rt}^u + H(\frac{2r_{\text{min}}}{w}) + 1 + \Delta \left( \bar{w}^u, \bar{d}^u \right) + e_i^t + \sum_{k=\max(n,e_i^t)}^{\min(n,\bar{e}_i^t)} \Delta \left( \bar{w}^{k-1}, \bar{w}^k \right), & \beta \left( e_i^t \right) = -1 \\
\bar{d}_{rt}^l + H(\frac{2r_{\text{min}}}{w}) + 1 + \Delta \left( \bar{w}^l, \bar{d}^l \right) + e_i^t + \sum_{k=\max(n,e_i^t)}^{\min(n,\bar{e}_i^t)} \Delta \left( \bar{w}^{k-1}, \bar{w}^k \right), & \beta \left( e_i^t \right) = 1 
\end{cases}
\end{align*}
\]

(19)

2.3.4. During the headland turns

The headlands are modelled as hypothetical “fields”, where there is a “relaxation” of the constrained traffic during the transport. The number of field tracks for these fields is \( a_u \) and \( a_d \) for the upper and the lower headland, respectively. The assumed fieldwork pattern is a continuous pattern \( (\sigma = 1, 2, \ldots, a_n) \). The lengths of the tracks are assumed to be the same for all tracks and are given by Eq. 4.

It is also assumed that the AU continues the application on the headlands area after the application on the main field body. Under this assumption, the tank capacity for the first route has to be equal to the remaining load after the last route in the main field body, which is equal to

\[
C_{\text{mt}}^l = C_m - d_f^l \omega
\]

(20)

where \( d_f^l \) has been defined in Eq. 9.

In the case of the RU being located in the opposite headland from the one where the AU operates, the AU must travel to the other headland following the track of the main field that is given by

\[
i^* = \arg \min_{i \in \mathbb{Z}} \left| \Delta \left( \bar{f}^s, \bar{d}^s \right) \right|
\]

(21)

2.3.5. Total non-effective distance

When the AU reaches the RU, it might have to execute a sequence of manoeuvres in order to be in a “refilling”

Fig. 5 – The GPS recordings for operation A.

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positioning. The distance corresponding to this manoeuvring is a stochastic quantity due to its dependence on factors such as the driver skills and available space. Let \( \bar{d_n} \) denote this distance. The non-effective distance during a route is given by

\[
d_{ne} = d_{ne}^{t} + d_{ne}^{f} + d_{ne}^{l} + \bar{d_n}
\]

while, the total non-effective distance for the whole operation is given by

\[
d_{ne} = \sum_{n=1}^{j} d_{ne}^{t} + \sum_{n=1}^{j'} d_{ne}^{f}
\]

(22)

Where the second term of the left part corresponds to the non-effective distance travelled during application in the headlands.

2.4. Field efficiency

For a quantitative estimation of the field efficiency of the simulated operation, information regarding the average velocities of the AU during the different parts of its motion (e.g., headland travelling, empty travelling, full load travelling, headland turning, applying) is needed as input for the model. However, for a more objective estimation of the efficiency of the system, the model is limited to simulating the distance based field efficiency that is given by the relation between the effective travelling distance (the distance that the AU travels while operating) and the total distance travelled by the AU:

\[
E_f = \frac{d_{ef}}{d_{ef} + d_{ne}}
\]

(23)

The field efficiency gives the key summarised output from the model. The principal architectural elements of the model leading to the operational efficiency are shown in Fig. 3. The a priori information includes the dimensions of the field, the material to be applied and the predicted machine performance. Based on this information, the route generation is carried out using the developed model covering the whole operation and providing for the estimation of the field efficiency based on distance travelled.

3. Experimental verification of the model

3.1. Materials and methods

For the evaluation and validation of the model, two field operations were monitored and analysed. The operations were assumed to be slurry applications carried out by a machinery system that includes an AU and a number of RU. A Massey Ferguson 4840 tractor was used, pulling a tank with 14.6 m³ capacity as the AU. A Massey Ferguson 6180 tractor pulling a tank with 14.6 m³ capacity was used as the RU.

Modifications of the machinery for CTF were based on a standardised basic working and track width. By using the combine harvester on the farm as the baseline, the basic working width was set at 6 m with a basic track width of 2.75 m. The track width of the combine harvester could be reduced from the normal 3.00 m using narrow tyres, while the track width of the large tractor carrying the heavy implements could be increased to 2.45 m. The remaining machinery items had a track width of 2.75 m.

Recording the operations involved logging of the position and the application status of the slurry applicator. As the data acquisition tool for the slurry applicator, a module comprising a TC65 Siemens Terminal\(^\text{®}\) (Germany, Siemens AG) with a built-in modem was connected to the implement computer for data extraction. This terminal encompasses a Java\textsuperscript{™} software development platform with a wide range of standard interfaces plus General Packet Radio Service (GPRS) class 12 functionality. Finally, a sensor was mounted on a switch indicating the on/off status of the trailing hoses. The sensor comprised a standard wheel sensor (2 nodded reed sensor), that is activated by a magnet. The sensor was mounted on the regulating lever, so that the magnet was activated when no slurry was applied. The customised sensor together with the GPS sensor, a Holux GR-213 (Denmark, Amitech.dk) capable of delivering a NMEA 0183 GGA string via a RS-232-compatible serial port, were connected to the terminal unit for wireless data transmission to a dedicated server configuration (Fig. 4, Sørensen and Thomsen, 2006).

The AU was constrained in-field operation with the loading of the tanker from the separate RU at the field headland. The RU was relocated to one of the field headlands in order for refilling to be carried out without headland travel or for the AU to travel outside of the field.

To implement the model, a program was developed using the MATLAB\textsuperscript{®} technical programming language.

3.2. Operation A

3.2.1. Experimental operation

The area of the field was approximately 4.9 ha (20 parallel field tracks) and nine routes in total were performed by the AU in order to complete the slurry application (including the application on the headland area) (Fig. 5). During the operation, the RU reached the field from the south field headland except for the last refilling that took place on the north field headland.

Table 1 - Measured data for operation A

<table>
<thead>
<tr>
<th>Route</th>
<th>Effective distance (m)</th>
<th>Transport distance (m)</th>
<th>Turning distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>978.25</td>
<td>591.05</td>
<td>74.59</td>
</tr>
<tr>
<td>2</td>
<td>801.57</td>
<td>784.72</td>
<td>43.84</td>
</tr>
<tr>
<td>3</td>
<td>940.36</td>
<td>684.14</td>
<td>44.68</td>
</tr>
<tr>
<td>4</td>
<td>1,031.90</td>
<td>588.49</td>
<td>80.07</td>
</tr>
<tr>
<td>5</td>
<td>933.37</td>
<td>276.83</td>
<td>30.63</td>
</tr>
<tr>
<td>6</td>
<td>916.27</td>
<td>231.34</td>
<td>63.08</td>
</tr>
<tr>
<td>7</td>
<td>879.61</td>
<td>579.77</td>
<td>197.38</td>
</tr>
<tr>
<td>8</td>
<td>870.12</td>
<td>456.15</td>
<td>56.65</td>
</tr>
<tr>
<td>9</td>
<td>899.2</td>
<td>700.38</td>
<td>320.34</td>
</tr>
<tr>
<td>Total</td>
<td>8,250.65</td>
<td>4,892.86</td>
<td>911.26</td>
</tr>
<tr>
<td>Total travelled distance (m)</td>
<td>14,054.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-working travelled distance (m)</td>
<td>5,804.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field efficiency (distance based) (%)</td>
<td>58.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Route 1: 20, 17, 19 (partial), Route 2: 16, 19 (partial), Route 3: 14, 18, 15 (partial), Route 4: 17, 12, 11 (partial), Route 5: 10, 11 (partial), Route 6: 8, 6, 7 (partial), Route 7: 5, 7 (partial), Route 8: 2, 4, 3 (partial), Route 9: 3 (partial), headlands.
Table 1 presents the measured data from the operation in terms of distances travelled.

3.2.2. Simulated operation A

The fieldwork pattern simulated by the model was formed by blocks consisting of five tracks in order to satisfy the preferred approach of the driver. This pattern results in the following track sequence $s = \{1, 4, 2, 5, 3, 6, 9, 7, 10, 8, \ldots\}$. Considering that the application was started from the north-east corner of the field (from track 20) this sequence is modified as $s_{\text{C138}} = \{20, 17, 19, 16, 18, 15, 12, 14, 11, 13, \ldots\}$. The refilling unit vectors for all the routes, except the last route, were given by $e_{\text{en}} = e_{\text{en}}(0, 0, 0)$. The vector for the last route was $e_{\text{el}} = e_{\text{el}}(r_0, 0, 1)$. The simulated output data from the model are depicted in Table 2.

### Table 2 – Simulated data for operation A

<table>
<thead>
<tr>
<th>Route</th>
<th>Effective distance (m)</th>
<th>Transport distance (m)</th>
<th>Turning distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>910</td>
<td>258.32</td>
<td>54.62</td>
</tr>
<tr>
<td>2</td>
<td>910</td>
<td>644.03</td>
<td>140.62</td>
</tr>
<tr>
<td>3</td>
<td>910</td>
<td>697.28</td>
<td>143.12</td>
</tr>
<tr>
<td>4</td>
<td>910</td>
<td>730.03</td>
<td>55.02</td>
</tr>
<tr>
<td>5</td>
<td>910</td>
<td>619.15</td>
<td>54.62</td>
</tr>
<tr>
<td>6</td>
<td>910</td>
<td>648.10</td>
<td>93.15</td>
</tr>
<tr>
<td>7</td>
<td>910</td>
<td>344.03</td>
<td>55.02</td>
</tr>
<tr>
<td>8</td>
<td>910</td>
<td>339.03</td>
<td>54.62</td>
</tr>
<tr>
<td>9</td>
<td>916</td>
<td>737.15</td>
<td>226.0</td>
</tr>
<tr>
<td>Total</td>
<td>8,196</td>
<td>5016.12</td>
<td>876.79</td>
</tr>
</tbody>
</table>

3.3. Operation B

3.3.1. Experimental operation

The field area was approximately 4.77 ha (23 parallel field tracks) and 10 routes in total were performed by the AU in order to complete the slurry application on the field (including the headland area) (Fig. 6). For each refilling event, the RU reached the field from the north field headland. Table 3 presents the measured data from the operation.

3.3.2. Simulated operation B

During the field operation, the AU initiated the slurry application with the remaining load after the completing the application from the previous operation. For this reason, the effective distance of the first route was about 133 m. In order to include this event into the model, the tanker capacity for the first route was set at 2.16 m$^3$ instead of 14.6 m$^3$.

Fig. 6 – The GPS recordings for operation B.
The simulated fieldwork pattern was formed by blocks consisting of four tracks resulting in the following track sequence: \( \sigma = (2.4, 1.3, [6.8.5.7], [10.12.9.11], \ldots) \). Considering that the application started from the north-east corner of the field (from track 23) this sequence is modified as \( \sigma = (22.20.23.21, [18.16.19.17], [14.12.15.13], \ldots) \). The simulated refilling locations were determined by the refilling unit vectors \( e_1^2 \rightarrow e_1^n (c, 0.1) \) \( \forall n \in \{1, \ldots, \lambda\} \). The data from the simulated output are presented in Table 4.

A comparison between the experimentally measured data and the simulated data shows that the model can simulate with sufficient accuracy the motion of an AU operating in CTF. As shown in Table 5, in predicting the total travelled distance, the error is 0.24% for operation A and 1.41% for operation B. The expected factor for field efficiency is the transport distance, since it contributes to 34.81% (operation A) and 29.52% (operation B) of the total travelled distance. In contrast, the headland turning, which constitute the dominant factor in the operation of conventional farming (Sørensen, 2003), according to the measured data only contribute to 6.48% and 5.27% of the total travelled distance. Therefore, the error in prediction of the non-working distance during headland turning is of less importance that the prediction of the transport distances.

### Table 3 – Measured data for operation B

<table>
<thead>
<tr>
<th>Route</th>
<th>Effective distance (m)</th>
<th>Transport distance (m)</th>
<th>Turning distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>133.39</td>
<td>541.32</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>972.41</td>
<td>290.51</td>
<td>58.75</td>
</tr>
<tr>
<td>3</td>
<td>924.11</td>
<td>351.92</td>
<td>60.07</td>
</tr>
<tr>
<td>4</td>
<td>957.37</td>
<td>323.86</td>
<td>55.77</td>
</tr>
<tr>
<td>5</td>
<td>950.37</td>
<td>334.75</td>
<td>57.79</td>
</tr>
<tr>
<td>6</td>
<td>934.31</td>
<td>350.48</td>
<td>59.87</td>
</tr>
<tr>
<td>7</td>
<td>914.00</td>
<td>345.42</td>
<td>138.3</td>
</tr>
<tr>
<td>8</td>
<td>868.74</td>
<td>443.73</td>
<td>52.26</td>
</tr>
<tr>
<td>9</td>
<td>679.03</td>
<td>436.15</td>
<td>77.54</td>
</tr>
<tr>
<td>10</td>
<td>436.51</td>
<td>99.54</td>
<td>67.87</td>
</tr>
<tr>
<td>Total</td>
<td>7,770.24</td>
<td>3,517.68</td>
<td>628.22</td>
</tr>
</tbody>
</table>

### Table 4 – Simulated data for operation B

<table>
<thead>
<tr>
<th>Route</th>
<th>Effective distance (m)</th>
<th>Transport distance (m)</th>
<th>Turning distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>133</td>
<td>532.54</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>910</td>
<td>309.47</td>
<td>57.5</td>
</tr>
<tr>
<td>3</td>
<td>930</td>
<td>343.31</td>
<td>71.61</td>
</tr>
<tr>
<td>4</td>
<td>910</td>
<td>380.31</td>
<td>65.01</td>
</tr>
<tr>
<td>5</td>
<td>910</td>
<td>316.31</td>
<td>45.54</td>
</tr>
<tr>
<td>6</td>
<td>910</td>
<td>366.75</td>
<td>71.61</td>
</tr>
<tr>
<td>7</td>
<td>910</td>
<td>359.07</td>
<td>72.01</td>
</tr>
<tr>
<td>8</td>
<td>910</td>
<td>342.31</td>
<td>71.61</td>
</tr>
<tr>
<td>9</td>
<td>910</td>
<td>361.43</td>
<td>90.9</td>
</tr>
<tr>
<td>10</td>
<td>378</td>
<td>341.00</td>
<td>94.29</td>
</tr>
<tr>
<td>Total</td>
<td>7,791</td>
<td>3,652.50</td>
<td>640.08</td>
</tr>
</tbody>
</table>

The main reason for this deviation between the measured and the predicted values arises from the preferences of the operator. The operator did not comply with the standard fieldwork pattern, but change the track sequence as well as the way that the RU was accessed. As an example, in the case of operation A the track sequence followed by the operator and as depicted by the model was:

- Actual: 20 → 17 → 19 → R → 16 → 19 → 15 → R → 13 → 12 → 11 → R → 10 →...
- Simulated: 20 → 17 → 19 → R → 19 → 16 → R → 18 → 15 → 12 → R → 14 →...

For most routes, there is no agreement between the actual and the simulated operation regarding the track from where the AU approaches the RU, as well as the first track that it reached after refilling. However, this change in fieldwork pattern caused deviations only on the portion of transport that concerned travelling in the headland. Consequently, the affect of the fieldwork pattern uncertainty on the model robustness is negligible.

An important point is that since the model itself includes the motion sequence generation for the operating machine, it can potentially constitute a part of the motion planning for an autonomous machine. The accurately positioned and permanent tracks in CTF provide advantageous conditions for implementing automatic systems and robotics.

Furthermore, the mathematical formulation of the operation captures the interrelationships and the interplay between features of the whole procedure. There were cases during the actual operation when the driver entered a new track with very low remaining load quantity that was only sufficient for application on a small part of the track. Consequently, the AU drove empty for a long distance on the current track, increasing the idle-transport time of the operation. In contrast, the driver could have avoided this if the decision was

### 4. Discussion

The errors in predicting transport distance for the two operations, as shown in Table 5, are 2.52% and 3.83%, respectively.
made to end the current route and drive to the RU. On the other hand, decisions like this may increase the number of the routes. The optimisation of this decision involves the optimisation of the material quantity that the AU applies at each route in order to minimise the total idle-transport distance and improve field efficiency. The mathematical model presented here can provide the basis for solving this deterministic optimisation problem. This is considered a subject for future research.

5. Conclusions

Detailed studies of driving patterns and sequence of motions for material handling operations using CTF in arable farming have formed the basis for the aggregation and development of a discrete-event model for predicting travelled distances. The validation of this model shows that this model can adequately predict the motion pattern of an AU operating in CTF. The error prediction, in terms of the total travelled distance, was 0.24%–1.41% for the 2 experimental setups. The key factor that influences field efficiency is the transport distance since it contributes between 29.52% and 34.81% of the total travelled distance. In the case of conventional farming, headland turnings constitute the determining factor for operational efficiency but, in this case, they only contribute between 5.27% and 6.48% of the total travelled distance.

The use of the developed model includes partial comparisons of studies of the change in the field efficiency between conventional farming and controlled traffic for various specifications of field size, field dimensions, wheel track layout, and so on. However, another potential use of the model includes motion generation for autonomous agricultural vehicles.

The current model structure provides significant knowledge on the interrelationships between mutual influencing parameters in the motion sequence and configurations of the CTF layout. Further researching into the model may include deterministic optimisation procedures for maximising the field efficiency for CTF farming operations.

Table 5 – Comparison between the data from the experimental and the simulated operation.

<table>
<thead>
<tr>
<th>Operation A</th>
<th>Measured</th>
<th>Simulated</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travelled distance (m)</td>
<td>14,054.77</td>
<td>14,088.91</td>
<td>0.24</td>
</tr>
<tr>
<td>Effective Distance (m)</td>
<td>8,250.65</td>
<td>8,196</td>
<td>0.66</td>
</tr>
<tr>
<td>Non-working distance (m)</td>
<td>5,804.12</td>
<td>5,892.91</td>
<td>1.53</td>
</tr>
<tr>
<td>Transport distance (m)</td>
<td>4,892.86</td>
<td>5,016.12</td>
<td>2.52</td>
</tr>
<tr>
<td>Turning distance (m)</td>
<td>911.26</td>
<td>876.79</td>
<td>3.93</td>
</tr>
<tr>
<td>Field efficiency (distance) (%)</td>
<td>58.7</td>
<td>57.52</td>
<td>2.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operation B</th>
<th>Measured</th>
<th>Simulated</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travelled distance (m)</td>
<td>11,916.14</td>
<td>12,083.58</td>
<td>1.41</td>
</tr>
<tr>
<td>Effective Distance (m)</td>
<td>7,770.24</td>
<td>7,791.00</td>
<td>0.27</td>
</tr>
<tr>
<td>Non-working distance (m)</td>
<td>4,145.90</td>
<td>4,292.58</td>
<td>3.54</td>
</tr>
<tr>
<td>Transport distance (m)</td>
<td>3,517.68</td>
<td>3,652.50</td>
<td>3.83</td>
</tr>
<tr>
<td>Turning distance (m)</td>
<td>628.22</td>
<td>640.08</td>
<td>1.89</td>
</tr>
<tr>
<td>Field efficiency (distance) (%)</td>
<td>65.21</td>
<td>64.48</td>
<td>1.12</td>
</tr>
</tbody>
</table>

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